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Implementation of Slip-Controller for Induction Motor Drive Employing Indirect Matrix Converter

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Abstract: A new scheme to design the proportional integral (PI) type controller for speed control of a constant Volts/Hz (V/F) three phase induction motor drive employing a matrix converter has been presented. An approximate linear model of induction motor operating in constant Volts/Hz scheme is derived and a design example of a slip controller for a three phase motor is presented. Performance of the designed controller is verified with results from simulation using Mat lab.

***Keywords*— Constant Volt/Hz, Matrix converter, Space vector PWM, VVVF, Induction motor drive.**

I. INTRODUCTION

Recent advances in power electronics and microprocessor technology have made it possible to commercialize sophisticated sensor-less Vector-Control and Direct Torque Control (DTC) schemes of induction motor speed control for low and medium power drive requirement. However Variable Voltage Variable Frequency (VVVF) drives using constant V/F principle remain a predominant choice over Field Oriented Control (FOC) and DTC drives for induction motor speed control in applications where the need of fast and smooth response to speed/torque change is not required, such as pumps, washing machines, ventilation blowers, etc. Using constant V/F control in these applications reduce the cost of extra current sensors and computational resources compared to FOC or DTC drives, while achieving the expected speed-torque control. The constant volts/Hz based VVVF drive principle is extensively documented in text-books and literature; however a method of designing slip-regulator using analytical approach is not described. Analytical approach for design of PI controllers for Field Oriented Control with parameter variations are presented in which can be used for design of slip controller for constant V/F drive but they are very complex and require accurate information of motor parameters. In this paper a step-wise design method is presented which is very simple and requires only the name-plate data of the motor. The design is verified with results from simulation using Matlab.

The control scheme of a typical constant V/F drive as shown in Fig. 1 relies on a PI-controller for regulating slip speed to compensate for the change in load torque at any operating speed. The design of PI-regulator is based on the gain constants, namely proportional gain, Kp, and integral gain, Ki, which are generalized by the drive manufacturer for a given rating of motor drive. However the optimum values of the controller gains are based on the actual rating of the motor, which is sometimes different than the rating of the drive. Hence re-tuning the PI controller to motor ratings justifies a better transient control capability and marginal improvement in efficiency.

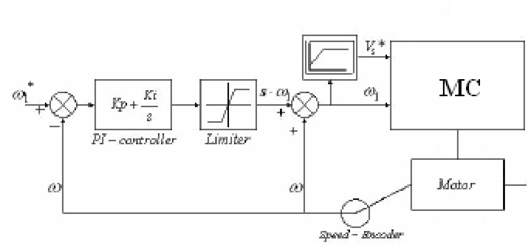

Figure1. Control scheme of closed-loop constant V/F Drive

MATRIX CONVERTER

A. Overview of a Matrix Converter

A general block diagram of a three-phase induction motor drive based on a matrix converter is shown in Fig. 2. The heart of this system is an array of nine bidirectional power switches (Fig. 3) which constitute the matrix converter itself, an input LC filter (with damping resistors connected in series or parallel with the inductors), and the induction motor. The power switches of the converter are controlled according to the commands given by the implemented modulation and commutation strategies. In this way, the voltage and frequency of the output voltages of the converter are continuously adjusted according to the requirements of the V/F which controls the induction machine.

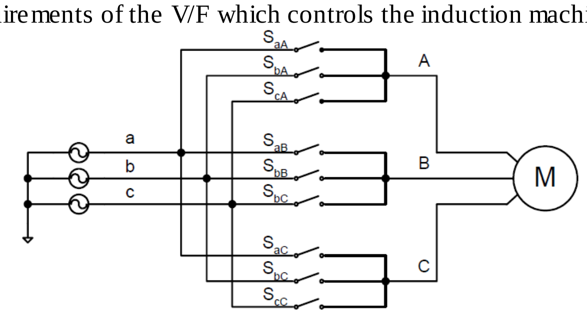

Fig 2. Matrix converter

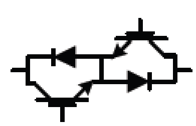

Fig 3 Bidirectional switch

B. Control of the Matrix Converter

The matrix converter is controlled with the aid of a modulation strategy. The one adopted in this work is the well known indirect space vector modulation. According to it, the matrix converter is viewed as a virtual system consisting of a rectifier stage

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connected to an inverter stage. The rectifier is controlled like a current source and the inverter is controlled like a voltage source. In both stages (rectifier and inverter), the switches are controlled using the classic Space Vector Modulation technique.
Taking into account the constraints imposed by the modulation strategy and safe operation of the matrix converter, each output line of the converter must be connected to a single input line at any time, that is:

$$S_{aj} + S_{bj} + S_{cj} = 1, \qquad j \in \{A, B, C\}$$

C. Indirect modulation principle

The object of the modulation strategy is to synthesize the output voltages from the input voltages and the input currents from the output currents. The three phase matrix converter can be represented by a 3 by 3 matrix form because the nine bidirectional switches can connect one input phase to one output phase directly without any intermediate energy storage elements. Therefore, the output voltages and input currents of the matrix converter can be represented by the transfer function **T** and the transposed T^T such as

$$\mathbf{V_O} = \mathbf{T} * \mathbf{V_I} \tag{1}$$

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} S_{aA} & S_{bA} & S_{cA} \\ S_{aB} & S_{bB} & S_{cB} \\ S_{aC} & S_{bC} & S_{cC} \end{bmatrix} \cdot \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{2}$$

$$\mathbf{I_I} = \mathbf{T}^T * \mathbf{I_O} \tag{3}$$

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} S_{aA} & S_{aB} & S_{aC} \\ S_{bA} & S_{bB} & S_{bC} \\ S_{cA} & S_{cB} & S_{cC} \end{bmatrix} \cdot \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \tag{4}$$

Where V_a ,V_b and V_c are input phase voltages, and V_A, V_B are V_C output phase voltages, I_a,I_b and I_c are input currents and I_A,I_B and I_C are output currents. The elements in the transfer matrix *Tij* represent the switch function from the instantaneous input voltage *Vi* to the instantaneous output voltage *Vj* and have to be assigned values that assure output voltages and input currents to follow their reference values. Defining a modulation strategy is actually filling in the elements of the transfer matrix. Although several Modulation strategies have been proposed since Venturini announced a closed mathematical solution for the transfer function **T** in early 1980, the indirect space vector modulation is gaining as a standard technique in the matrix converter modulations.

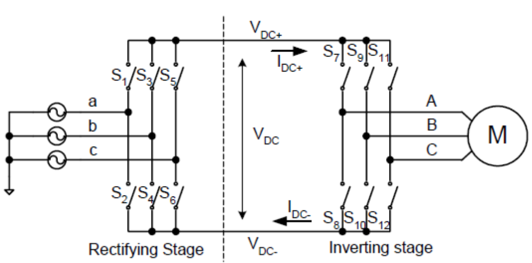


Fig 4 Equivalent circuit of indirect matrix converter

The indirect space vector modulation (indirect SVM) was first proposed by Borojevic et al in 1989 where matrix converter was described to an equivalent circuit combining current source rectifier and voltage source inverter connected through virtual dc link as shown in Fig. 4. Inverter stage has a standard 3φ voltage source inverter topology consisting of six switches, *S7 ~ S8* and rectifier stage has the same power topology with another six switches, *S1 ~ S6*. Both power stages are directly connected through virtual dc-link and inherently provide bidirectional power flow capability because of its symmetrical topology. Although this equivalent circuit has provided a strong platform to analyze and derive several extended PWM strategies specified in a certain application since then, it is still ambiguous for a beginner to grasp its operating principle. The operating principle of the indirect SVM will be illustrated with graphical approach.
The basic idea of the indirect modulation technique is to decouple the control of the input current and the control of the output voltage. This is done by splitting the transfer function **T** for the matrix converter in (2) into the product of a rectifier and an inverter transfer function.

$$\mathbf{T} = \mathbf{I} * \mathbf{R}$$

$$\begin{bmatrix} S_{aA} & S_{bA} & S_{cA} \\ S_{aB} & S_{bB} & S_{cB} \\ S_{aC} & S_{bC} & S_{cC} \end{bmatrix} = \begin{bmatrix} S_7 & S_8 \\ S_9 & S_{10} \\ S_{11} & S_{12} \end{bmatrix} \cdot \begin{bmatrix} S_1 & S_3 & S_5 \\ S_2 & S_4 & S_6 \end{bmatrix} \tag{5}$$

Where the matrix **I** is the inverter transfer function and the matrix **R** is the rectifier transfer function. This way to model the matrix converter provides the basis to regard the matrix converter as a back-to-back PWM converter without any dc-link energy storage. This means the well know space vector PWM strategies for voltage source inverter (VSI) or PWM rectifier can be applied to the matrix converter.
Substituting (5) in (2),

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} S_7 & S_8 \\ S_9 & S_{10} \\ S_{11} & S_{12} \end{bmatrix} \cdot \begin{bmatrix} S_1 & S_3 & S_5 \\ S_2 & S_4 & S_6 \end{bmatrix} \cdot \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} S_7 \cdot S_1 + S_8 \cdot S_2 & S_7 \cdot S_3 + S_8 \cdot S_4 & S_7 \cdot S_5 + S_8 \cdot S_6 \\ S_9 \cdot S_1 + S_{10} \cdot S_2 & S_9 \cdot S_3 + S_{10} \cdot S_4 & S_9 \cdot S_5 + S_{10} \cdot S_6 \\ S_{11} \cdot S_1 + S_{12} \cdot S_2 & S_{11} \cdot S_3 + S_{12} \cdot S_4 & S_{11} \cdot S_5 + S_{12} \cdot S_6 \end{bmatrix} \cdot \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{6}$$

The above transfer matrix exhibits that the output phases are compounded by the product and sum of the input phases through inverter switches *S7 ~ S12* and rectifier switches *S1 ~ S6*. The first row of (6) represents how output phase *A* is built from the input phase *a*, *b* and *c* and this mathematical expression can be interpreted again in the graphical viewpoint. If the equivalent circuit is seen from the inverter output phase *A*, two switches *S7* and *S8* of phase *A* half bridge is directly connected to input phases *a*, *b* and *c* through six rectifier switches *S1 ~ S6*. Fig.5 shows how the switch set of equivalent circuit can be transformed into the relevant switch set of the nine bidirectional switched matrix converter in the case of phase *A* and gives an basic idea that the duty cycles of the matrix converter branch can be derived by multiplying the duty cycles of the corresponding rectifier and inverter switches in the equivalent circuit. Therefore

the indirect modulation technique enables well-known space vector PWM to be applied for a rectifier as well as an inverter stage.

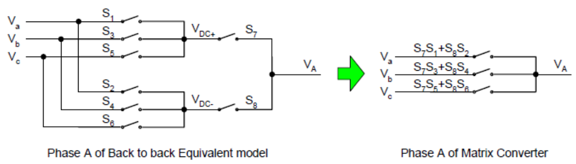


Fig 5 Transformation from equivalent circuit to matrix converter phase A.

SLIP REGULATOR DESIGN

A. Slip Control Scheme

Constant Volts/Hz or scalar control of induction motor refers to the scheme of controlling the motor torque and speed by proportionally varying the voltage with supply frequency to maintain air-gap flux constant and achieve up to rated torque at any speed by controlling the slip-speed.

Neglecting magnetizing inductance, torque developed in an induction motor can be expressed as:

$$T_e = \frac{\frac{|V|^2}{\omega_1} \cdot \frac{R_2}{s}}{\left(R_1 + \frac{R_2}{s}\right)^2 + (X_1 + X_2)^2}$$

Where, V=per phase voltage applied to the stator, $\omega 1 = 2.\pi.f1$, f1 is the supply frequency, p=pole pairs, R1 and R2 = stator and rotor resistance and X1 and X2 = stator and rotor reactance, s = slip. Under normal operating conditions, the slip is small implying

$$\frac{R_2}{s} >> R_1, \ \frac{R_2}{s} >> (X_1 + X_2)$$

Hence the developed torque can be approximated as:

$$T_e = \frac{|V|^2}{\omega_1^2} \cdot \frac{s \cdot \omega_1}{R_2}$$

From (2) it can be seen that

$T_e \ \alpha \ s.\omega_1$ if $\frac{V}{\omega 1}$ is kept constant, torque developed could be controlled by controlling the slip speed $s.\omega_1$

The constant volts/Hz control scheme is shown in fig 18.The speed reference ω_1^* is compared with the actual speed of the motor ω and the error signal is given as input to the PI controller. The output of the PI controller is the commanded slip speed s.ω_1 which is summed up with the actual speed of the motor ω to generate the synchronous speed ω_1 frequency command. The voltage command to the inverter is fed through a V/Hz profile graph to keep the V/F ratio constant. The error difference of reference and actual speed is processed through the slip regulator defined by the proportional gain, Kp, and integral gain, Ki, to generate slip speed. The values of these gain constants determine the performance of drive.

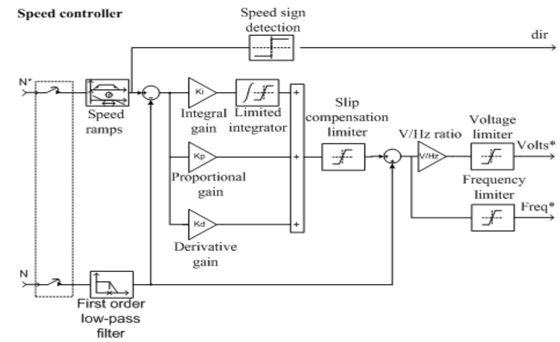


Fig.18 Schematic of speed controller.

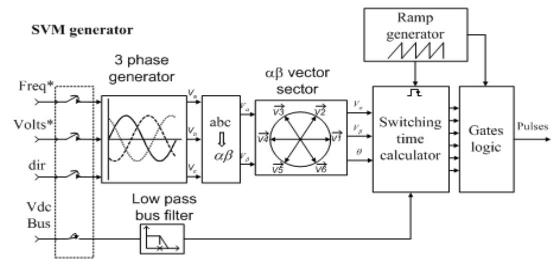


Fig.19 Generation of pulses from speed controller.

B. Linearised model of induction machine constant V/F drive using PI slip regulator.

From (21), it can be deduced that to control the torque developed by motor, the slip speed needs to be controlled. An Induction motor drive system using a PI-controller to regulate speed can be modeled as shown in figure 20.

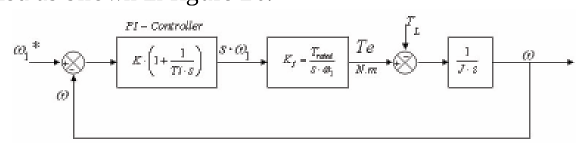


Fig.20 System model of IM for slip regulator design.

The speed reference is ω_1^*rad/sec. The output of the PIcontroller is the controlled slip-speed, depending on the difference of reference speed and actual speed. Neglecting the electrical transients, the torque developed can be considered proportional to slip-speed.

$$T_e(s) = K_f \cdot s \cdot \omega_1$$

The rotor speed is

$$\omega(s) = (T_e - T_L) / J \cdot s$$

Where J is the moment of inertia of the motor.

The open loop transfer function of the system assuming the load torque is zero, can be given by

$$A(s) = \frac{K(1 + T_i \cdot s) \cdot K_f}{(T_i \cdot s) \cdot (J \cdot s)}$$

Where, $K_f = \frac{T_{rated}}{s \cdot \omega_1}$

PI controller constants K and Ti can be calculated using conditions

$$|A(j\omega_c)|=1$$

$$\phi_c = 180^o + \tan^{-1}(\omega_c \cdot T_i) - 90^o - 90^o$$

$$K = \frac{T_i \cdot J \cdot (\omega c)^2}{K_f \cdot \sqrt{1+(T_i \cdot \omega_c)}}$$

$$T_i = \frac{\tan(\phi_c)}{2 \cdot \pi \cdot f_c}$$

Where $\emptyset_c$ is the phase margin and $\omega_c = 2\pi f_c$, where f_c is cross over frequency. Assume ideal phase margin of the system $\emptyset_c$= 60 degree and cross over frequency is 1/3 of speed sensor frequency. The PI controller gains Kp and Ki can be calculated as

$$K_p = K \text{ and } K_i = K/T_i$$

II. SIMULATION RESULTS

Simulation of the Drive was made using Matlab-Simulink and SimPowerSystems Toolbox. The scheme of the drive simulated is shown in figure 22. Back-propagation method is used to realize the digital PI controller.

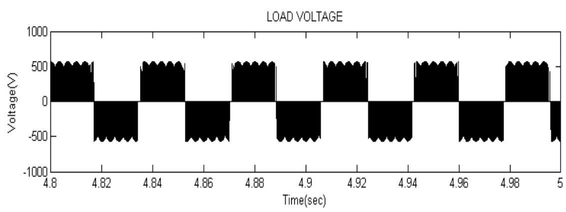
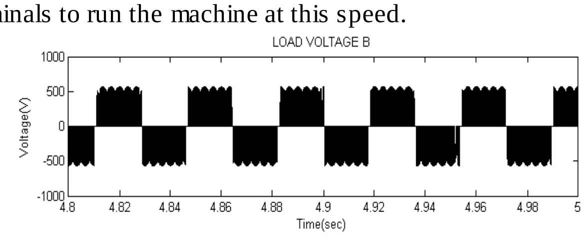
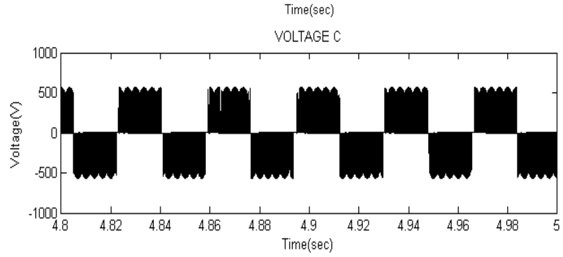


Fig 21 Matrix converter output voltage for the reference speed of 800rpm.

A reference speed of 800 rpm is set and the rated load torque is applied. Fig 21 shows the voltage that is available at the machine terminals to run the machine at this speed.





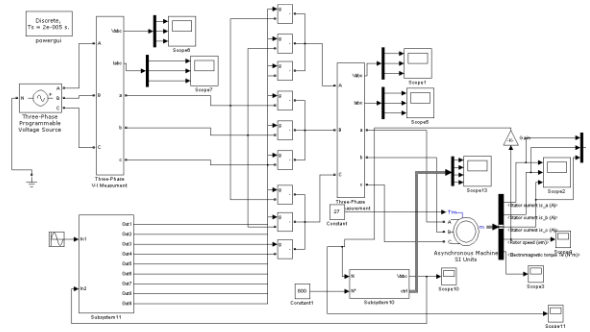


Fig.21a Scheme of matrix converter controlled IM drive

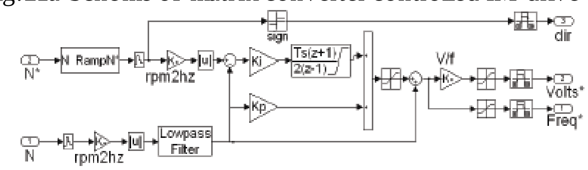


Fig.21b PI Controller discretized using back propagation method

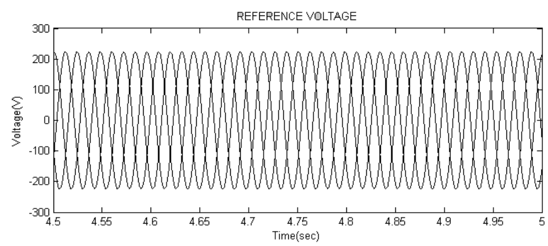


Fig.22 Reference voltage available at the converter terminals.

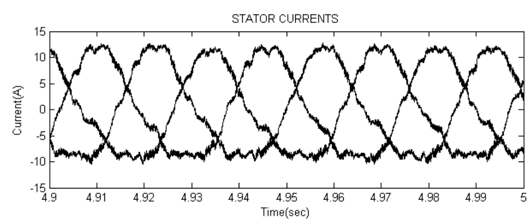


Fig.23 Stator currents of the machine.

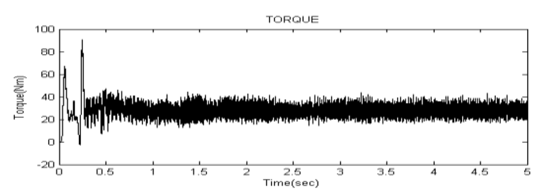


Fig.24 Torque

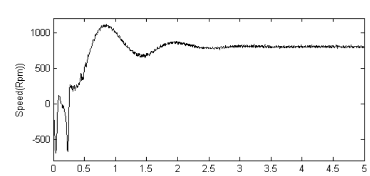


Fig.25 Machine speed.

From fig 25 it can be seen that the machine speed is settling at the reference speed set externally.

The controller performance is also verified by applying a step change in the reference speed. For a step change in the reference

speed from 800 rpm to 1000 rpm at time t=5sec, the various waveforms are shown with rated torque applied.

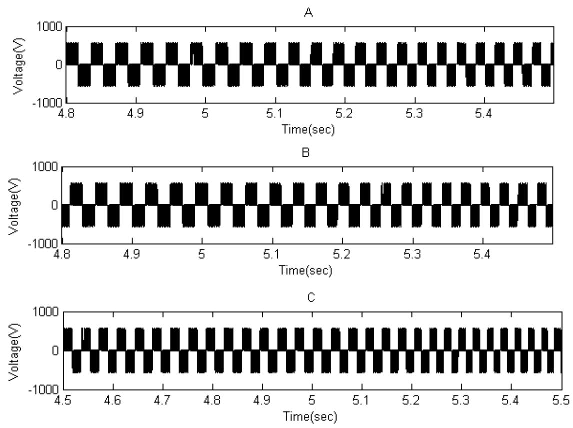


Fig.26 Three phase converter output voltage.

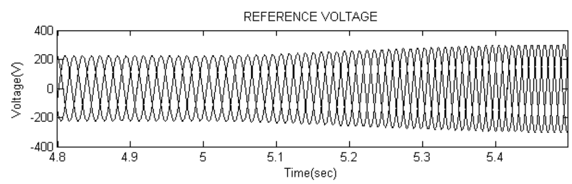


Fig.27 Reference voltage variation.

From fig 27 it can be seen that the reference voltage changes for the change in the reference speed set. The reference voltage at 800 rpm is 214V whereas at 1000 rpm it is 350V.The frequency is also changed to maintain constant V/F

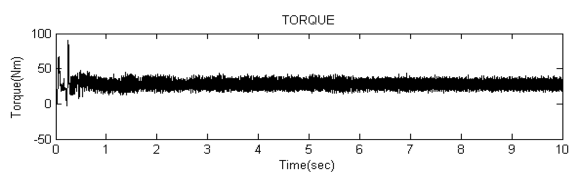


Fig.28 Torque

The rated torque of 27Nm is applied constant throughout the speed variations. The variation of machine speed is shown in the fig.29. The speed settles at the desired value because of the controller action.

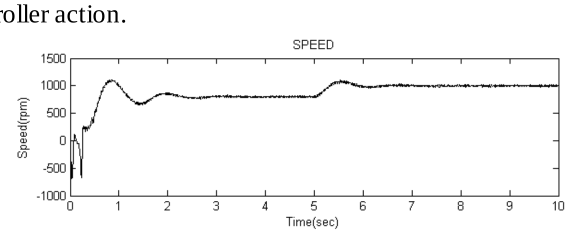


Fig.29 Machine speed

CONCLUSION

An analytical method of designing PI-controller using the motor name-plate details for speed control of a constant V/F controlled induction motor drive has been presented and an approximate linear model of induction motor drive when operating under constant V/F control has been derived. The drive response with the designed PI-controller has been successfully verified with simulation results. Satisfactory performance is observed at low-speed and high speed operation of the drive during load transients. The designed PI-controller demonstrated effective control of the motor speed at start-up and speed-reversals without causing any undesired over-shoot of speed. It is felt that with lower speed sensor cut-off frequency the design procedure can be extended to even lower operating speeds of the motor.

III. APPENDIX

The ratings of the three phase 50 Hz, 400 V, 4 kW, delta connected, 1,430 rpm squirrel cage induction motor are:

$R_s = 1.405\Omega$,$R_r' = 1.395\Omega$,$L_s = 0.005839H$

$L_r' = 0.005839H$,J = 0.0131 Kgm2,

F = 0.002985Nms, Poles = 4

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V. BIOGRAPHIES

K.Ganesan is working as Assistant professor in the department of Electrical and Electronics engineering in Vel Tech University, Chennai. His areas of interests include Power electronics for renewable energy, Flexible AC transmission and Drives.